2
Instrumental developments

High-Resolution Soft X-ray Emission Studies Using a Transmission-Grating Spectrometer

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Introduction

Soft x-ray emission studies in combination with synchrotron radiation sources have been a subject of increasing and broad interest as it provides information on the electronic structure on gas, liquid and solid materials. We have previously reported our new design of a transmission-grating spectrometer (TGS) for high resolution soft X-ray emission studies [1]. The optical design incorporates the basic concept for x-ray imaging and spectroscopy telescopes [2] into a compact and easy-to-use layout with higher energy resolving power. One of the advantage of the present TGS is its high light gathering capability without sacrificing the energy resolution, which is enabled by the introduction of the Wolter type-I mirror and the transmission grating (TG).

The present TGS is installed in the soft x-ray emission spectroscopy (XES) endstation of the undulator beamline BL3U of the UVSOR facility. In this report we describe the apparatus and its performance.

Optical Design and Apparatus

The present optical layout is a modification of the Rowland torus mount with facet gratings [1]. The design is adopted by Chandra x-ray satellite observatory. In the ideal Rowland torus mount, the facet TGs should be mounted onto Rowland torus while keeping their normal to point the focus of the incoming x-rays. In the present spectrometer, the facet TGs are positioned onto a single Si wafer. Such simplification may degradess optical properties. However, we demonstrated by ray-tracing simulations that the aberration in the geometry of the present spectrometer is small enough to realize the energy resolving power better than 5000 [2].

The TGS is pictured in Fig. 1. The soft x-rays emitted from the sample are collected by a type I Wolter mirror with a magnification of 10. The Wolter mirror is a tube-shaped composite mirror with hyperboloidal and elliptical inner-surfaces, which are 27 and 33 mm long, respectively. The incident anlge of 89 degree at the interconnection of the two mirror surfaces yields an acceptance angle as large as 1.5×10^{-3} sr. The slope error for each mirror estimated by the imaging property was better than 2.0 mrad rms [3]. The collected soft x-rays with a focus of 1500 mm downstream of the interconnection of the two mirror surfaces are dispersed by a transmission grating with a groove density of 6250 lines/mm. The transmission grating manufactured by NTT-ATN is made of silicon carbide and has a free-standing structure with a thickness of 800 nm. A detector together with the transmission grating and the focus of the 0^{th} order diffraction is positioned on a circle with a radius of 719.5 mm. The detector consists of a CCD (e2v CCD 42-40-A33) with a 2048 x 2048 pixel format with 13.5 x 13.5 mm and a preamplifier (Meisei Co.) inside the vacuum chamber. After the installation of the optical elements, the CCD chamber and the pipe between the CCD detector and the TG are baked at 100 °C. The pressure in the chamber is in the 10^{-7} Pa range.

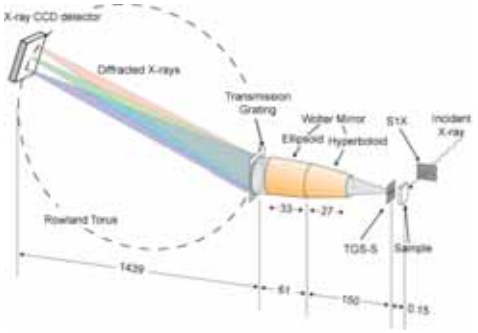

Fig. 1 Schematic layout of the transmission-grating spectrometer at the XES endstation of the undulator beamline BL3U.

The spectrometer is installed at the XES endstation of the undulator beamline BL3U. Schematic layout of the XES endstation of the undulator beamline BL3U is illustrated in Fig. 2 [4]. A soft x-ray emission spectrometer generally requires small beam size at the sample position, because a smaller opening of the spectrometer entrance slit is needed to achieve higher energy resolution. Beamline BL3U is designed to give small beam size of order of 10 x 40 μm^2 by placing sample 23 mm downstream of the beamline exit slit, S1X. This configuration is enabled by the constant exit-arm length of BL3U, where the x-rays from the undulator are dispersed by one of three plane varied-line-spacing grating, which have central groove densities of 240, 600, and 1200 lines/mm. The distance between the grating and the focal plane is 2703 mm. The slit opening as small as 10 μm diffracts soft x-ray significantly. The typical vertical beam size is 5-20 μm depending on the photon energy and the energy resolution of the incident x-rays. In the horizontal direction, the focusing mirror

M2X of the XES endstation images the undulator source with a demagnification of 23.4. Under operating condition, the horizontal beam profile has a gaussian profile with FWHM of 41.2 μm

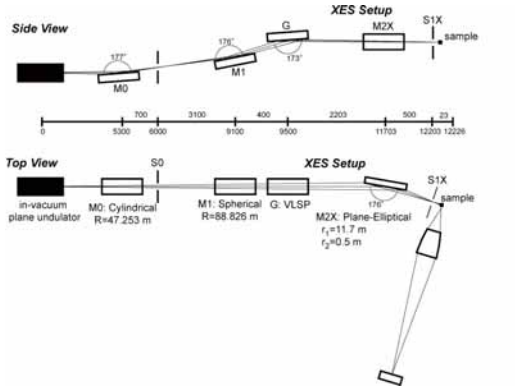

Fig. 2 Schematic Layout of XES endstation of the undulator beamline BL3U.

Results and Discussion

The stray light contamination is estimated by measuring the profile of the 0th order diffraction. Typically the stray light intensity is less than 1 % of the 1st diffraction order intensity. The energy resolution is estimated by measuring diffuse scattering from aluminum sample illuminated by 60 eV soft x-rays. Fig. 3 shows 1st order diffraction peak. The peak width was FWHM of 3 pixels, which corresponds to the energy resolving power of 4600. To our knowledge, the achieved resolving power by using TG is more than 4 times higher than the best record reported so far [5].

The spectrometer was employed to measure resonant XES spectra of a single crystal of silicon. The sample is illuminated with a grazing-angle of 20 degree. Fig. 4a shows the Si L-edge absorption spectrum of the sample together with the excitation energies. An image of the CCD detector taken by exciting at the resonance d is shown in Fig.4b. The vertically dispersed image where the lower direction corresponds to the higher photon energy clearly shows a sharp elastic peak with two bumped structure due to the x-ray emission. Horizontal length of the signal band is confined within about 1 mm, which is a magnified image of the sample area where the incident soft x-rays illuminated. Fig. 4c shows the XES spectra excited at the resonances, where each spectrum was taken within 30-120 min. with incident soft x-ray flux of 10^{11} photons/sec. The entrance slit opening was 20 μm. The spectrum clearly shows coherent and incoherent structure as reported in the previous work [6].

These results indicate that the present TGS is capable of carrying out high-resolution soft x-ray emission studies. Although rather low photon density is used in the current experiment, the results clearly show that the XES study is feasible with the present TGS. Large acceptance angle will give an advantage to the studies of organic samples where the sample damage is frequently problematic as well as the higher resolution studies which was out of the reach by using conventional x-ray emission spectrometers.

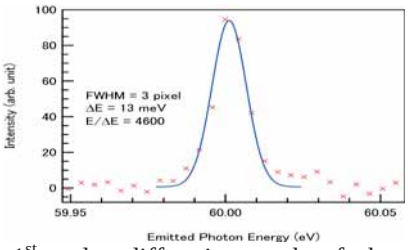

Fig. 3 1st order diffraction peak of the diffuse scattering from aluminum sample. Energy resolving power of 4600 is demonstrated.

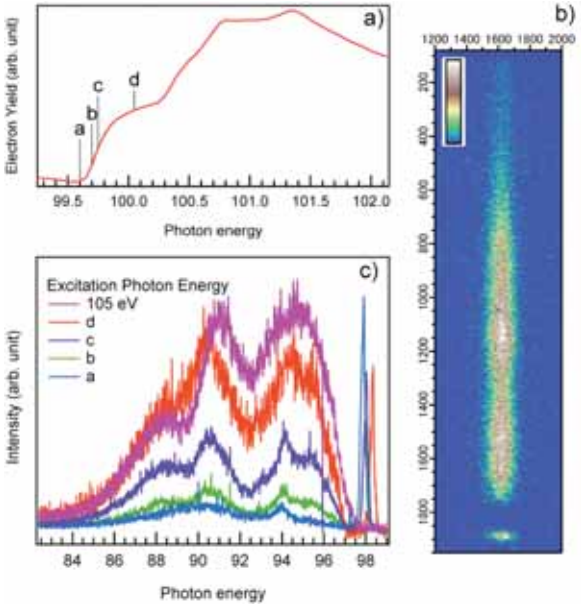

Fig. 4 Si L-edge Absorption spectra (a), and a CCD detector image when excitated at the resonance d.The labels a-d shows the excitation energies applied in resonant XES spectra (c).

Acknowledgements

The authors gratefully thank NTT-ATN, Hamamatsu Photonics, and Meisei Co. for the development of the TG and the Wolter mirror, and CCD electronics, respectively. This work is partly supported by the Japan Society for the Promotion of Science (JSPS), Special Coordination Funds for Promoting Science and Technology (MEXT), and International Collaboration Program (IMS).

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BL2B

Construction of an End Station of BL2B to Study the Dissociative Photoionization of Fullerenes and VUV Spectroscopy of Ionic Liquids

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A new vacuum chamber for the end station of beam line 2B (BL2B) in UVSOR was constructed. The chamber was designed for the gas phase spectroscopy of refractory materials such as fullerenes, metallofullerenes and ionic liquids. The following three subjects are now under way: (1) the velocity map imaging of the ionic photofragments from fullerenes [1, 2], (2) threshold photoelectron – photoion coincidence measurements of the fullerenes, and (3) photoelectron and photoabsorption spectroscopy of ionic liquids.

Drawing of the chamber is shown in Fig. 1. The twofold μ-metal shield is put inside the chamber to prevent penetration of the geomagnetic field. The effective volume surrounded by the shield is five times as large as that of the previous chamber used at BL2B. The new chamber is equipped with 14 ports facing the ionization region, i.e. the focal point of the synchrotron radiation. This larger volume and versatile port arrangement enable us to incorporate many complicated devices. We designed this chamber to adapt not only to BL2B but also to BL7U. In order to compensate the difference of the heights of optical axes, we placed a stage of 50 cm in height at BL2B and put the chamber on the stage. Additionally the chamber was mounted on a micromotion stage to align its optical axis readily with the beam lines when the chamber is relocated.

The installation of the chamber at BL2B was accomplished. We observed TOF spectra of fragments and parent ions produced by the dissociative photoionization of fullerenes (C_{60}). We have obtained spectra using the previous setup at BL2B. In comparison with signal intensities and resolutions of these spectra, we can examine the performance of the new setup. The TOF spectrum at the photon energy of 90 eV obtained by the new setup is shown in Fig. 2. Intense three peaks in the spectrum correspond to C_{60}^{+}, C_{60}^{2+} and C_{60}^{3+} parent ions. Progressions of small peaks in shorter TOF side of doubly and triply charged parent ion peaks are fragments which lost C_2 units successively. From these results, we concluded that we succeeded in reproducing the results obtained with the previous setup.

Using the chamber with small modifications of signal processing electronics, we can perform more quantitative experiments than those using the previous setup. Prior to the new subjects (1) - (3), we resumed quantitative comparison of photoion yield spectra between the fullerene and higher fullerenes (C_{70} [3], C_{84}). This will give us a clue to understand extraordinary stability of fullerenes. Moreover, in the energy range available using BL7U (6 – 40 eV), the fullerenes have strong absorption (> 100 Mb) associated with structures which originate from molecular nature of the fullerenes. Although a part of the structure was observed using BL2B, it is subtle because the structure is out of practical coverage of the monochromator of BL2B. Observation of the fullerene absorption spectra in the energy range of BL7U using the new chamber will enable us to understand the ionization mechanism of fullerenes.

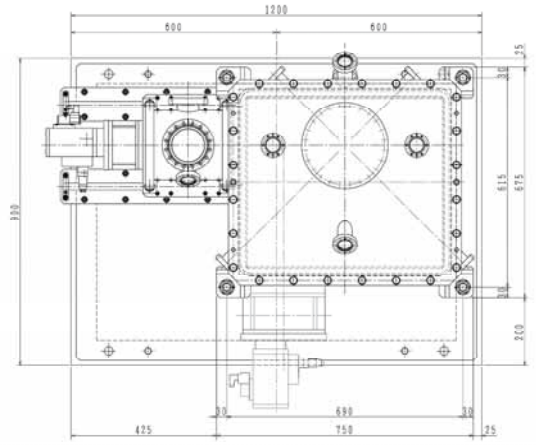

Fig. 1 Top view (drawing) of a new chamber for the end station of BL2B in UVSOR. Numbers in the figure are in mm.

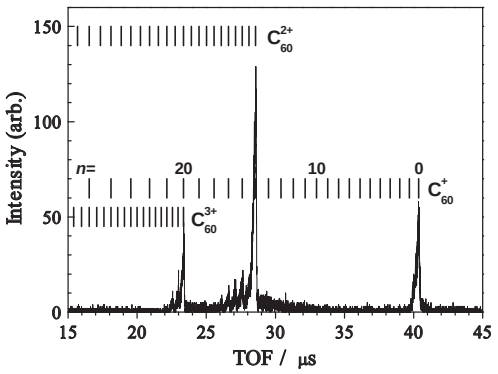

Fig. 2 TOF mass spectra of ions produced by the dissociative photoionization of the fullerene (C_{60})

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The Development of Sub-Pixel Spatial Resolution to Soft X-rays Using Electron-Multiplying CCD Detectors

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Introduction

We have developed a transmission-grating spectrometer (TGS) for high-resolution soft-X-ray emission studies. This spectrometer is designed to realize a resolution E/ΔE beyond 5000 in the energy region of 50-600 eV with a high throughput. One of the key optical elements for this spectrometer is the charge-coupled device (CCD) detector. Here we report the development and performance of the CCD detector. The transmission grating has lower linear dispersion compared with reflection gratings. The detector is mounted in normal incidence geometry in order to obtain high quantum efficiency. These configurations demand the detector to have spatial resolution better than 5 μm. By measuring the center of the electron charge cloud generated in depletion layer of CCD, sub-pixel resolution detection was demonstrated for hard x-rays by Hiraga et.al [1]. In the case of soft X-rays, one photon produces a charge cloud, of which the total intensity is about 10 times weaker than hard x-rays (20-300 electrons). In order to analyze the centroid of the charge cloud, the intensity of the nearby pixels (1-10 electrons) must be accurately measured. This requirement is out of the reach of the conventional scientific CCD. In this study, we have introduced electron multiplying CCD technology in order to reduce the effective readout noise substantially lower than the intensity of the charge cloud tail, while increasing the readout rate as high as 400 kHz/pixel (10 frame/sec).

Experimental

The CCD detector is assembled with an un-coated back illuminated CCD sensor with L3Vision technology (CCD97-00) with 16 x 16 μm square pixels. The active area is 512 x 512 pixels (8.2 x 8.2 mm^2). The sensor is cooled by thermoelectric coolers and mounted on a conflat flange. The assembled and finely tuned CCD is illuminated by soft x-rays from the undulator beamline BL3U. The CCD detector is operated at 400 kHz/pixel (10 Hz/frame) readout rate with electron multiplication of about 100.

Results and Discussion

In the spectroscopic application, the one dimensional spatial resolution is of interest. Therefore, the CCD detector was operated in the binning mode of 4x1 pixels. The size of the charge clouds is evaluated by illuminating monochromatic soft x-rays from the undulator beamline BL3U. The spatial resolution has been estimated by measuring soft x-rays (380 eV) transmitted through 10 micron slit (Fig. 1a). Single pixel events are rejected as they originate from thermal electrons. Centroid in serial transfer direction (horizontal direction in Fig. 1) of all events that are spread over more than 2 pixels are analyzed. The resulting image is shown in Fig. 2b. The distance between the slit and the CCD sensor was 1.62 mm, which causes diffraction from the edge of the slit. The line profile across the slit image was simulated based on the Fresnel theory assuming the Gaussian profile of the point spread function (PSF) of the detector. By fitting the experimental results (Fig. 2), we obtained the PSF of the detector with FWHM of better than 3 μm, which represents 1/5th of a pixel resolution.

Acknowledgements

The authors gratefully thank Peter Pool (e2v) and e2v for the provision of the un-coated back-illuminated L3V sensors. This work is partly supported by Special Coordination Funds for Promoting Science and Technology (MEXT), and International Collaboration Program (IMS).

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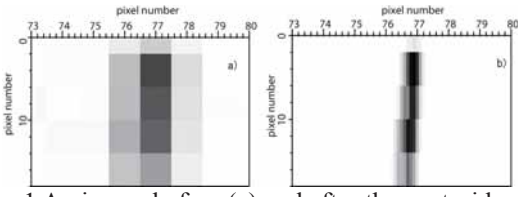

Fig. 1 An image before (a) and after the centroid analysis (b).

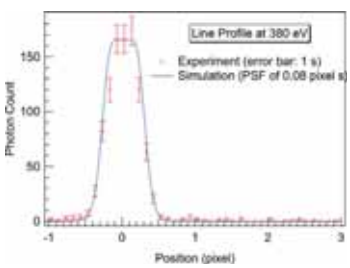

Fig. 2 Experimental line profile across the 10 μm slit image after the centroid analysis (+) and simulated line profile (blue line).

BL4B

Performance of the Double Toroidal Electron Analyzer for Electron-Ion Coincidence Experiments

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A double toroidal electron analyzer (DTA) has been constructed for realizing electron-ion coincidence experiments. It has been planned to study the decay dynamics of core-excited or ionized molecules by using the DTA with an ion momentum imaging spectrometer. The molecule with a core hole is very unstable due to its high internal energy and subsequent electronic relaxation processes often lead to dissociation. A correlation analysis among the particles ejected during the relaxation process gives access to proper understanding on the decay dynamics. Detailed descriptions of the electron-ion coincidence spectrometer and the DTA had already been given elsewhere [1-3]. The DTA is suitable for electron-ion coincidence experiment because of its high angular acceptance (5% of 4π sr) and moderate energy resolution (less than 1% of the pass energy) for electron analysis. Additionally, the DTA allows the angular distribution measurement of electrons, with the use of a two-dimensional position sensitive detector (PSD: Roentdek DLD40).

Prior to the coincidence experiments [4], we have evaluated energy resolution achieved by the DTA under the present condition. The experiment was performed at soft x-ray beamline BL4B with an energy resolving power $E_{ph}/\Delta E_{ph}$~800 at 300 eV photon energy. We have detected Ne 2*s* photoelectrons for the performance test. The sample gas was effused through an aperture of 0.2 mm diameter on the repeller plate. The photoelectrons ejected at 54.7° with respect to the electric vector of the photon beam were analyzed in energy. The DTA pass energy E_{pass} was set to 200 eV which allows the simultaneous observation of electrons with the energy range of 248 - 270 eV. Photoelectron spectrum was deduced from the electrons' arrival positions on the PSD.

Figure 1(a) shows a Ne 2*s* photoelectron image obtained at 302.6 eV. A concentric circle on the image corresponds to the photoelectrons. The anisotropic intensity along the circumference of the circle results from the unevenness of the transmission efficiency. The radial intensity distribution corresponding to the photoelectron spectrum is shown in Fig. 1(b). A least square fit with a Gauss function gives the peak width of 1.34 eV (FWHM). Considering the monochromator bandwidth, the instrumental energy resolution is estimated to be ΔE=1.3 eV (FWHM), which corresponds to the resolving power of the DTA $E_{pass}/\Delta E$=154. We have measured Ne 2s photoelectron spectra by changing the photon energy and estimated the resolving power. In Fig. 2, the electron energy resolution and the resolving power are plotted as a function of the kinetic energy. The resolving power better than 100 is achieved within an energy range corresponding to 7% of the pass energy. For the lower/higher kinetic energy electrons, the resolving power is somewhat worse than that for 254.1 eV electrons, which results from an imperfection of the electric field at the exit plane of the toroidal surfaces.

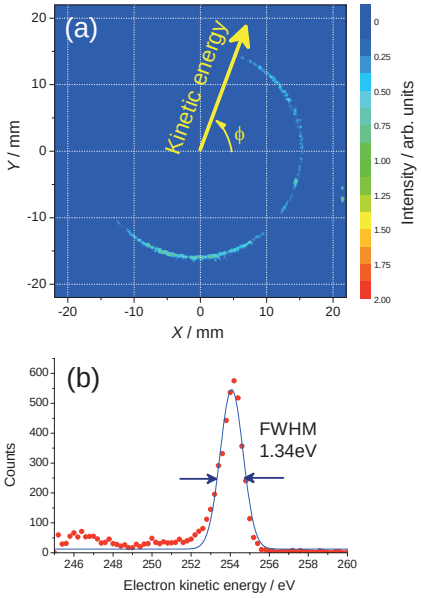

Fig. 1 (a) Two-dimensional image of Ne 2*s* photoelectrons measured at 302.6 eV photon energy. (b) Ne 2*s* photoelectron spectrum deduced from the image.

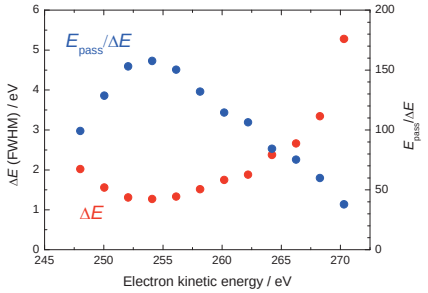

Fig. 2 The energy resolution and resolving power of the DTA plotted as a function of the kinetic energy.

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BL5B

Measurement of Absolute Efficiency for Micro Channel Plates by Using Pure-Calibrated EUV Beam

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Introduction

We study to optically observe the Earth's plasmasphere, which is filled with cold plasmas (mainly H^+, He^+, O^+ and electrons). The He^+ and O^+ ions have resonance scattering emission lines in the extreme ultraviolet (EUV) region, at 30.4nm (HeII) and 83.4nm (OII) respectively. The intensity of each emission is proportional to column density of each scattered particle under the assumption of the optically thin condition.

The SELenological and ENgineering Explorer (SELENE) satellite will be launched in 2007 and put into the orbit around the moon. The Telescope for EXtreme ultraviolet light (TEX) of the Upper atmosphere and Plasma Imager (UPI) onboard the SELENE satellite will observe the plasmasphere at 30.4nm and 83.4 nm lines from the lunar orbit. In this experiment, in order to calibrate the sensitivity of the UPI-TEX we measure the quantum efficiency of the micro channel plates (MCPs), which we use as the standard detector, at 30.4nm line.

Measurement and Result

We install an Al/Mg/Al (744Å/3958Å/747Å) filter on the entrance of the SOR beam to eliminate the multi-order lines from the 30.4nm line with PGM35. At first, we investigate the purity of the 30.4nm line through the Al/Mg/Al filter. We judge the purity from the consistency between the wavelength characteristics of an Al/C (1201Å/54Å) filter and an Al/Mg/Al (744Å/3958Å/747Å) filter for the particular lines at the EUV facilities of Institute of Space and Astronautical Science (ISAS) and those for the continuous lines at UVSOR. The former is measured for the emission lines of the gas (He, Ne) with the discharge light source. Fig. 1 shows the transmittances of the two filters measured at ISAS and UVSOR. It is clear that both profiles of each filter are consistent in the wavelength region of 25-50nm. We interpret from the result that the pure 30.4nm can be introduced through the Al/Mg/Al filter by using PGM35.

With the available pure 30.4nm line, then we measure the quantum efficiency of the MCPs. The quantum efficiency is calculated by the rate of the MCPs count to the electron yield of the photo diode which is absolutely calibrated. The result of the measurement shows that the quantum efficiency of the MCPs is 7.4% at 30.4nm line.

As the next step, in addition to the 30.4nm line, we plan to measure the quantum efficiency at the 83.4nm line, which is another observational object of UPI-TEX. Then the purity of 83.4nm line is essential, and must be investigated for the next machine time.

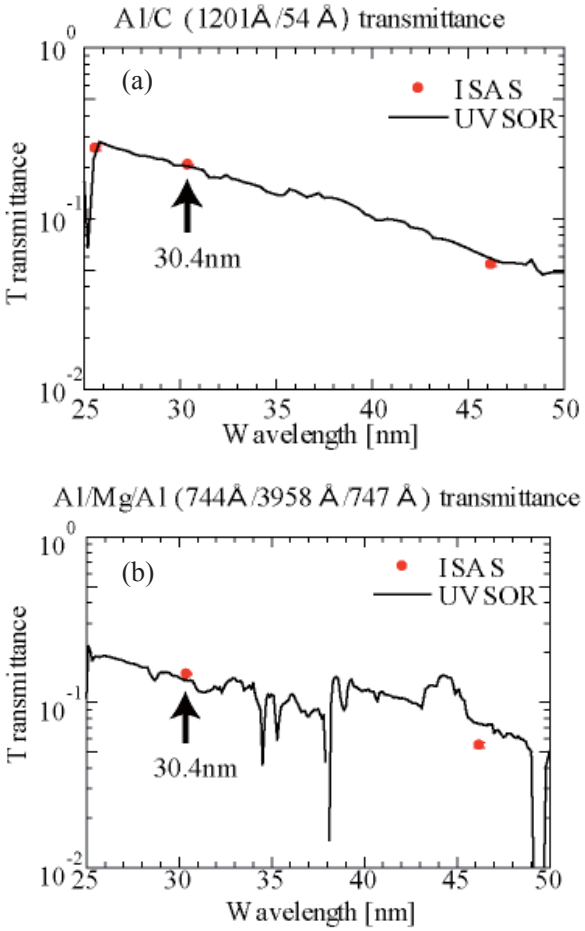

Fig. 1 The transmittances of (a) an Al/C (1201Å/54Å) filter and (b) an Al/Mg/Al (744Å/3958Å/747Å) filter. The red dots show the results of the measurements at the EUV facility of ISAS and the solid lines show those at UVSOR. The solid line in (b) is discrete at 38nm and 49nm because the incident beam introduced by PGM35 is weak at the wavelengths and the results have large error.

BL5B

Calibration of Optics for Extreme Ultra-Violet Region

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Introduction

We're developing a new spectrometer in order to measure the high-order harmonics in vacuum ultra-violet (VUV) and extreme ultra-violet (XUV) generated in ultra-intense laser-plasma interactions. Optical system of spectrometer for VUV/XUV light should compose of reflective optics which are spherical mirror (SM) and spherical grating mirror (GR) because the harmonics can not propagate in the transmittive optics for examples CaF_2 (cut-off 120 nm) and MgF_2 (cut-off 115 nm). We investigated the reflectivity of SM and the ±1st diffractivity of GR.

Experimental

We utilize SM (ACTON Research Corp. #1200-VUV coating) and GR (Horiba Jovin Yvon monochrometer concave grating) for the spectrometer. These properties are shown in Table 1 and Table 2. As varying the incident angle, the dependence of reflectivity of SM and the ±1st diffractivity of GR on pump wavelength were measured using s-polarization synchrotron radiation of multi-bunch operation at BL5B line with a photodiode (IRD AXUV-100). In the experiments, we measured the reflected light from spherical optics irradiating into the photodiode aperture monitoring maximum photodiode currents.

Table 1. Properties of spherical mirror [1].

Coating	Wavelength	Reflectivity
Al - MgF_2	115 – 300 nm	70 -90 %

Table 2. Properties of spherical grating mirror [2].

Coating	Groove density	Deviation
Al - MgF_2	1200 gr/mm	64 deg

Results and Discussion

Reflectivities of SM for the harmonics from 9th (@117 nm) to 15th (@70.2 nm) with s-polarization incidence are shown in Fig. 1. It is found that our results are significantly different from Ref. [1]. Also at the smaller incident angle, the difference of reflectivity becomes larger by the wavelength. In addition reflectivity of 9th is insensitive to the incident angle compared with 13th (@75.2 nm).

The ±1st diffractivities of GR for the 9th to 15th harmonics with s-polarization incidence are shown in Fig. 2 and Fig. 3. Only the +1st relative diffractivities from 100 to 300 nm were calculated and this calculation shows particularly decrease from 100 to 140 nm in Ref. [2]. Our experiment found that the ±1st difrractivity roughly increased with shorter wavelength.

The experiments were carried out using s-polarization light. However, it is well known that reflectivity and difrractivity hardly depend on polarization in VUV/XUV region light [3]. From the results, we can evaluate the total optical loss for the spectrometer.

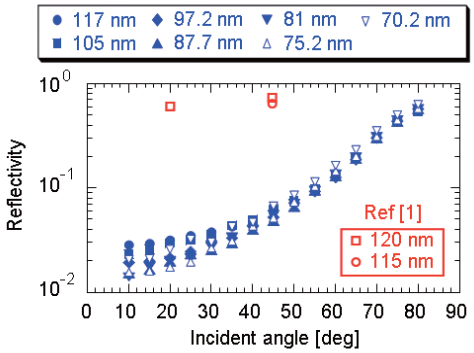

Fig. 1 The reflectivity of SM was measured using s-polarization synchrotron light.

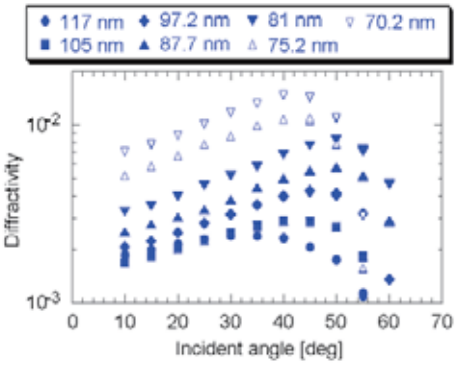

Fig. 2 The -1st diffractivity of GR was measured using s-polarization synchrotron light.

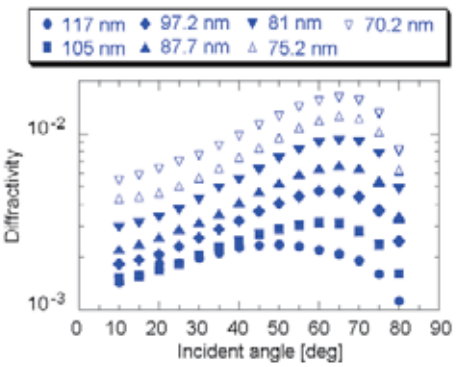

Fig. 3 The +1st diffractivity of GR was measured using s-polarization synchrotron light.

[1] Catalog, ACTON Research Corp.
[2] Catalog (Ref. 522 00 250), Horiba Jobin Yvon.
[3] C. Palmer, "Diffraction grating handbook (fifth edition)", Thermo RGL, 2002.

BL5B

Calibration of Phosphors for Extreme Ultra-Violet Region

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Introduction

We're developing a new spectrometer in order to measure the high-order harmonics in vacuum ultra-violet (VUV) and extreme ultra-violet (XUV) generated in ultra-intense laser-plasma interactions. Instead of expensive light detector such as a micro-channel plate (MCP) and a charge coupled device (CCD), we utilized phosphors (Zn_2SiO_4:Mn, $BaMgAl_{10}O_{17}$:Eu) for plasma display panel of that property is well known above VUV (λ>120 nm) region. We experimentally evaluated luminous fluorescent characteristics at the shorter wavelength from the rear side of the phosphor films in the condition of actual uses.

Experimental

The sample films on the glass plate are made by the coagulation sedimentation method. The properties are shown in Table 1. Measurements of luminous fluorescent spectra and quantum efficiency dependence on pump wavelength were measured using synchrotron radiation of multi-bunch operation at BL5B line. Each property was measured with a spectrometer (Jobin Yvon HR320) and a photodiode (IRD AXUV-100).

Table 1. Properties of phosphor sample films.

Sample	Thickness	Fluorescent center
Zn_2SiO_4:Mn	30 um	9.03 % (Mn)
$BaMgAl_{10}O_{17}$:Eu	50 um	9.31 % (Eu)

Results and Discussion

Luminous fluorescent spectra of phosphors were shown in Fig. 1 and Fig. 2. In spite of different pump wavelength, the luminous fluorescence spectra show no difference between VUV/XUV and over 120 nm [1]. It is clear that it is impossible to distinguish the pump wavelength from the spectra in uses an imaging detector for VUV/XUV region.

Luminous fluorescent quantum efficiency of phosphors excited by VUV/XUV light corresponding to the high order harmonics is shown in Fig. 3. T luminescent fluence for both phosphors is estimated by multiplying the simulation results of harmonics intensity at 20 J/ 10^{19}W/cm^2 laser (@1.05 um) light irradiated to a solid target [2], resulting that the luminescence of 210 mLux for 105 nm (10th harmonic) can be detected with 144 msr solid view angle. As the result, it experimentally examines that the harmonics could be measured with phosphors because a general astronomical CCD, which has more than a few mLux sensitivity, could detect the VUV/XUV harmonics.

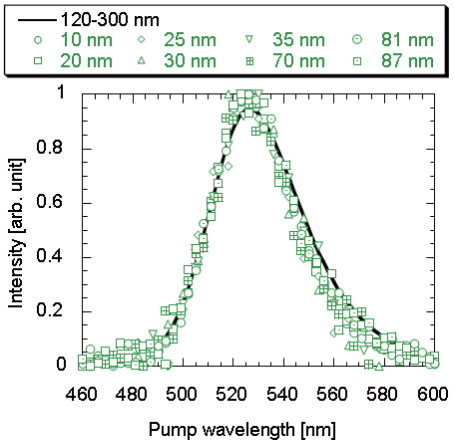

Fig. 1 Luminescence spectra of Zn_2SiO_4:Mn excited by VUV/XUV region light of synchrotron radiation.

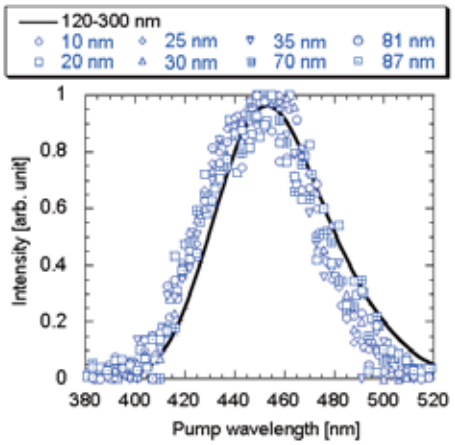

Fig. 2 Luminescence spectra of $BaMgAl_{10}O_{17}$:Eu excited by VUV/XUV region light of synchrotron radiation.

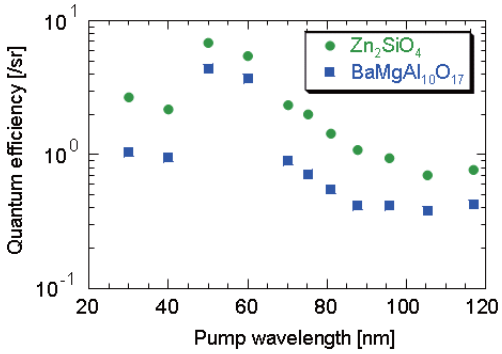

Fig. 3 Quantum efficiency of phosphors excited by VUV/XUV region light of synchrotron radiation.

[1] Catalog, Kasei Optonix LTD.
[2] P. Gibbon, Phys. Rev. Lett. **76** (1996) 50.

BL7U

Construction of a VUV Angle-Resolved Photoemission Beamline BL7U

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Recently, the energy resolution of photoemission experiments is drastically improved by using helium discharge lamps and VUV lasers. Due to the improvement, the thermodynamical properties of solids can be understood by the change of the electronic structure detected by photoemission. In the case of the angle-resolved photoemission spectroscopy (ARPES) using such light sources, the momentum along the normal direction of sample surface (k_z) cannot be set at a high symmetry point because the excitation photon energy that directly connects to k_z cannot be tuned. To determine the three-dimensional band structure at the high symmetry points by ARPES with tunable photons is important to compare with the band structure calculation. Since synchrotron radiation (SR) is suitable for the use of the various photon energies, some photoemission beamlines have been constructed in the world up to now. Because of the low photon flux of SR, however, the energy-resolution in ARPES was lower than the other sources mentioned above. Then we constructed a new undulator beamline in the VUV region at UVSOR-II for the purpose of the high-energy resolution ARPES with the total energy resolution less than 1 meV in the whole excitation energy of 6 - 40 eV and with the various (vertically / horizontally linear and circular) polarizations of photons.

We employed a various polarized APPLE-II-type undulator light source [1], a Wadsworth-type VUV monochromator [2] and a high-energy-resolution photoelectron analyzer with a liquid-He-cooled cryostat with 6-axes manipulator. Since the Wadsworth monochromator has no entrance slit and the light source size (2σ) of $0.04(H)\times1.2(H)$ mm^2 in the 1-% coupling machine operation of UVSOR-II [3], the VUV light with high photon flux and with high energy resolution can be obtained. The overall picture of the beamline is shown in Fig. 1. The undulator radiation is guided to 10-m-radius spherical gratings by two plane mirrors (M0, M1). The light is focused on the exit slit (S) by the spherical gratings. The monochromatized light is focused again on a sample by a toroidal mirror (M3). Because of no entrance slit, the photon flux on the sample becomes very high. However the near-normal incident mirror M1 reduces the photon flux in the higher energy region. Then we employed changeable nine mirrors including Mo/Si multilayer mirrors which have high reflectivity in the photon energy range of 30-40 eV to increase the photon flux [4].

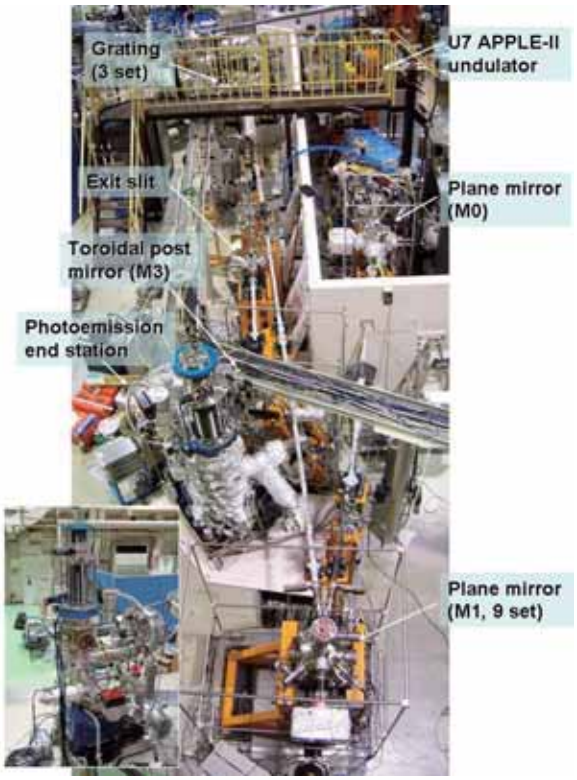

Fig. 1. Top view of the VUV photoemission beamline BL7U of UVSOR-II.

[1] S. Sasaki, K. Miyata, and T. Takada, Jpn. J. Appl. Phys. **31**, L1794 (1992).
[2] S. Kimura, T. Ito, E. Nakamura, M. Hosaka, and M. Katoh, AIP Conf. Proc. **879**, 527 (2007).
[3] M. Katoh, M. Hosaka, A. Mochihashi, J. Yamazaki, K. Hayashi, Y Hori, T. Honda, K. Haga, Y Takashima, T. Koseki, S. Koda, H. Kitamura, T. Hara, and T. Tanaka, AIP Conf. Proc. **705**, 49 (2004).
[4] T. Ejima, A. Yamazaki, T. Banse, K. Saito, Y Kondo, S. Ichimaru, and H. Takenaka, Appl. Opt. **44**, 5446 (2005).

Performance Test of The VUV Monochromator at BL7U

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BL7U is a new VUV undulator beamline at UVSOR-II constructed in FY2006. The main purpose of the beamline is to elucidate the origin of the exotic physical properties of functional materials including strongly correlated electron systems by determination of the electronic structure by an angle-resolved photoemission experiment. To perform the experiment, both of the high energy resolution and high photon flux of the monochromatized light are simultaneously required. Then we checked the energy resolution and the photon flux at the same monochromator condition with the exit slit size of 100 μm.

The energy resolution is tested by using rare gases. The helium 1*s np* ($h\nu \sim 24.5$ eV) and argon $3s3p^6$ *np* ($h\nu \sim 29$ eV) absorption lines are shown in Figure 1. The helium absorption spectrum was recorded using the grating (3600 lines/mm) for the highest energy range. The energy resolution was evaluated to be $E/\Delta E > 19{,}000$. On the other hand, the argon spectrum was obtained by using the medium region grating (2400 lines/mm) and the energy resolution was $E/\Delta E > 9{,}000$.

The obtained and the geometrically calculated energy resolution are plotted in Figure 2. The energy resolution of this beamline depends on the electron beam parameter of the storage ring, particularly, the beam size at the emission point. At present, the storage ring is operated with 5-% coupling. The obtained energy resolutions at 24.5 and 29 eV are higher than the calculated lines. In the top-up operation, the coupling percentage will be reduced to 1 %. Then the energy resolution becomes 2.2 times higher than the 5-% coupling operation because of the reduction of the electron beam size.

With the same beamline parameter, the photon flux was obtained as shown in Figure 3. The spectra were recorded by using the different undulator gap size, two M1 mirrors, Au and SiC and different gratings. If the quantum efficiency of the gold film is assumed to be 5 %, the photon flux at $h\nu = 10$ - 22 eV is more than 10^{12} ph/sec at 200 mA beam current. In the energy region above 30 eV, the intensity rapidly decreases with increasing photon energy because of the poor reflectivity of gold. In the energy region, we will employ four Mg/SiC multilayer mirrors.[1] Since the reflectivity is about a few 10 times higher than that of a gold film, the photon flux in the energy region will recover to at least 10^{11} ph/s.

[1] T. Ejima et al., Appl. Opt. **44** (2005) 5446.

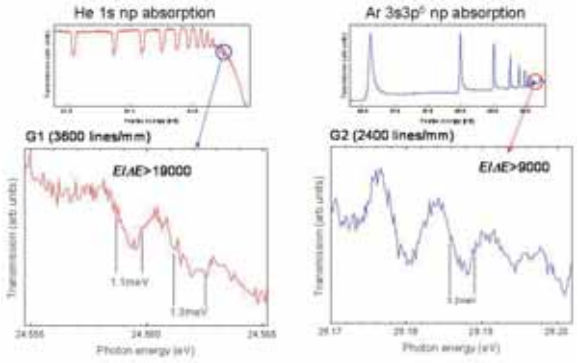

Fig. 1. Absorption spectra of helium and argon gases with the exit slit size of 100 μm. The narrowest width of the absorption lines is regarded as the energy resolution.

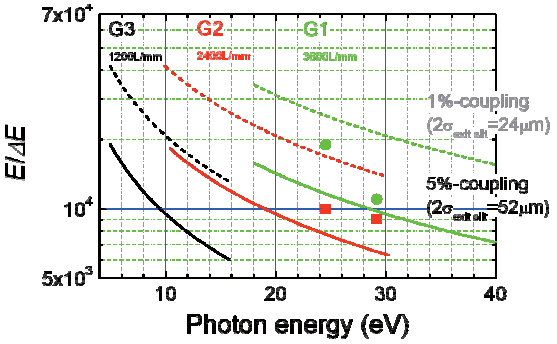

Fig.2. Experimentally evaluated (marks) and calculated (lines) energy resolution ($E/\Delta E$) of three installed gratings as a function of photon energy and the coupling of the electron beam. The present coupling is 5 %.

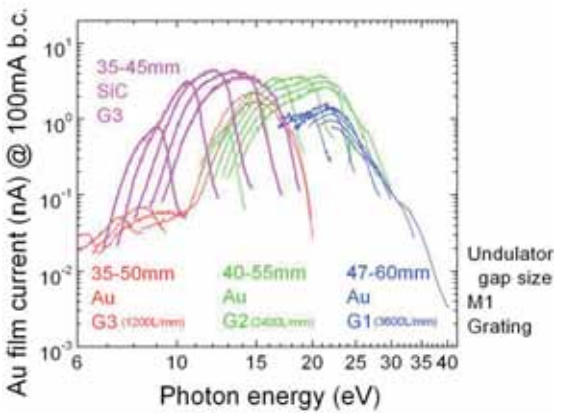

Fig. 3. The throughput spectra of BL7U detected by a drain current of a gold film. The undulator gap, M1 mirrors and gratings are changed. The exit slit size was 100 μm.

BL7U

Performance of the Three-Dimensional VUV Angle-Resolved Photoemission Apparatus at BL7U

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The investigation of the anisotropic interaction at the Fermi surface (FS) of inter-metallic compounds, namely "Fermiology", is one of the most facilitating research field in recent days, since the interactions between carriers, local spins, and lattice vibrations play a dominant role for the functionality (superconductivity, magnetism, etc.) of materials. Angle-resolved photoemission (ARPES) spectroscopy is a powerful tool to observe the quasiparticles which form FS's. The recent technological innovation of synchrotron radiation instruments makes that it is possible to observe three-dimensional (3D) FS's [1]. However, there are few 3D-ARPES apparatuses meeting demands of high-energy/momentum resolution, enough bulk-sensitivity, and high-photon-flux in the world.

To investigate the anisotropic interaction at FS of solids, we have constructed a bulk-sensitive three-dimensional angle-resolved photoemission apparatus (Fig. 1) using VUV light with high-energy resolution and high photon flux from an undulator beamline BL7U at UVSOR-II [3]. The main part of the apparatus consists of a 200-mm-radius hemispherical photoelectron energy analyzer (MBScientific AB; 'Peter' A-1) and a liquid-helium flow cryostat with 6-axes manipulation system (R-dec Co. Ltd.; i-Gonio). To obtain ARPES spectra along high-symmetry lines of a sample, the sample manipulator is equipped with three-independent rolling mechanism; two of them are rotations (θx and θy) with respect to the sample surface normal and the other an in-plane rotation (ϕ). In addition, to be feasible to obtain a complete data set, not only of FS, but also of quasi-particle band dispersion within 12 hours (e.g., user beam operation time in a day), we will develop a computational multidimensional scanning system.

Finally, we briefly introduce the present performance of the PES measurement. From the energy-distribution-curve of evaporated gold at the Fermi level (Fig. 2(a)), the total energy resolution with the angle-integrated mode is about ΔE_{Total} = 1.5 meV with $h\nu$ = 10 eV photons at T = 15 K. The horizontal spot size on the sample estimated from the position distribution curve (Fig. 2(b)) is about 0.5 mm.

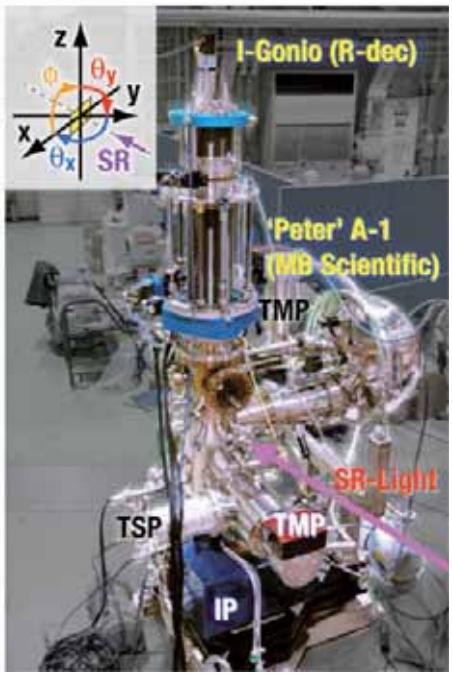

Fig. 1. Three-dimensional VUV angle-resolved photoemission apparatus at BL7U. Purple arrow indicates a path of SR light. Inset shows the definitions of 6-axes of the manipulater.

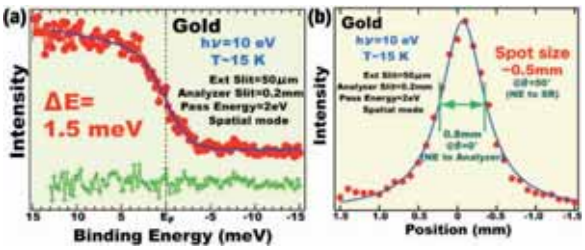

Fig. 2. Energy- (a) and position- (b) distribution curves of gold at the Fermi level at T = 15K obtained by using $h\nu$ = 10 eV photons.

[1] T. Ito *et al.*, J. Mag. Magn. Mater. **310**, 431 (2007).

[2] S. Kimura *et al.*, AIP Conf. Proc. **879**, 527 (2007).